School of Physics

Course Outline 2021

PHYS4143

Topics in Contemporary Physics (Honours)

School of Physics

Faculty of Science

T2, 2021

1. Staff

Position	Name	Email	Consultation times and locations	Contact Details
Astrophysics Lectures	Dennis Stello (Coordinator) A/Prof Kim-Vy Tran	d.stello@unsw.edu.au Kimvy.tran@gmail.com	Consultation time by arrangement via email	(02)
General Relativity Lecturers	(Coordinator) Dr Jan Hamann Yvonne Wong	j.hamann@unsw.edu.au Yvonne.y.wong@unsw.edu.au	Consultation times: by arrangement via email	(02)
Quantum Field Theory	Dr Michael Schmidt (Coordinator) Dr Oleg Tretiakov	m.schmidt@unsw.edu.au o.tretiakov@unsw.edu.au	Consultation times: by arrangement via email	(02)
Quantum Matter and Information	Prof Susan Coppersmith (Coordinator) Prof Michelle Simmons	s.coppersmith@unsw.edu.au m.simmons@unsw.edu.au	Consultation times: by arrangement via email	(02) 9385 4553
Journal Club	Prof Paul Curmi (Coordinator) A/Prof Julian Berengut	p.curmi@unsw.edu.au julian.berengut@unsw.edu.au	Consultation times: by arrangement via email	(02) 9385 7637
Teaching Support Officer	Zofia Krawczyk-Bernotas	z.krawczyk-bernotas@unsw.edu.au	School of Physics office G06, Old Main Building	(02) 9065 5719

2. Course information

Units of credit: 6
Pre-requisite(s): PHYS4141 Quantum Mechanics (Honours), and PHYS41412 Statistical Physics (Honours)

Teaching times and locations:
http://timetable.unsw.edu.au/2021/PHYS4143.html

2.1 Course summary

Students will take two of the four lecture modules offered in astrophysics; general relativity; quantum field theory; and quantum matter, information and computing.

The Advanced Astrophysics module develops in-depth knowledge of topics in modern Astrophysics and equips students with a modern toolset to engage in cutting-edge research. Students obtain a core understanding of the physics of relevant equations and develop fundamental physics intuition. Topics include: radiative transfer; exoplanets; asteroseismology; interstellar medium and star formation; galaxy formation and evolution; cosmology; time-domain astrophysics; statistical techniques.

The General Theory of Relativity is Einstein's geometric theory of gravitation that unifies the Special Theory of Relativity and Newton's law of gravitation. This first course in General Relativity will provide an introduction to non-Euclidean geometry, Einstein's equation; spherically symmetric solutions of Einstein's equations (Schwarzschild solution), the weak field limit; Gravitational collapse, black holes; linearised gravity, gravitational waves and their production and observation; Friedmann-Lemaitre-Robertson-Walker cosmology, the standard hot Big Bang model.

Quantum Field Theory is an important tool in many branches of theoretical physics. In fundamental physics, the QFT framework combines special relativity and quantum mechanics to explain the subatomic structure of matter and the physics of the early universe. In condensed matter physics, it provides a quantum description of many-body systems. This first course in QFT comprises an introduction to classical field theory, the Euler-Lagrange equations and Noether's theorem, the Dirac and Klein-Gordon equations, the quantisation of free scalar, vector and spinor fields; and a selection of topics drawn from covariant perturbation theory, the S-matrix and Feynman diagrams; the computation of elementary processes in quantum electrodynamics; field theory approach to phase transitions; dimensional reduction in classical criticality; critical indexes in low-dimensional systems; non-linear sigma-model and topological solutions.

Quantum Matter, Information and Computing will introduce students to quantum computing, the physics of superconducting devices, the Quantum Hall and other topological effects in materials, and the basics of Fermi liquid theory. Advanced topics will include Andreev scattering at semiconductor-superconductor interfaces and Majorana fermions, fractional quantum Hall effect, graphene and the two-dimensional Dirac equation.

Journal Club

Each student will be assigned a paper (the papers will represent key advances in physics that will be of interest to any serious physicist.). Students will make a 20-minute presentation that covers the background, the advance and its implications. Every member of the class will be expected to at least read the paper. The presenter will then lead a discussion (~20 minutes) of the work.

2.2 Course aims

Students in this course will study a range of topics in modern physics. This will provide students with a broad and comprehensive understanding in these areas and a foundation for further study and research. Students will gain skills in analysing current research literature and presenting their analysis in a seminar.

2.3 Course learning outcomes (CLO)

1. Recall and demonstrate understanding of core principles of selected topics in physics, such as general relativity, astrophysics, quantum field theory and Quantum Matter, Information and Computing

2. Develop an ability to analyse and solve a wide range of problems in areas such as general relativity, astrophysics, quantum field theory, quantum matter and information andcomputing
3. Communicate disciplinary knowledge and research findings in oral form.
4. Analyse and evaluate selected peer reviewed journal articles; demonstrate an ability to recognise the important points and explain these to peers.

2.4 Relationship between course and program learning outcomes and assessments

Course learning outcomes 1-3 are assessed in the 4 assessment tasks. These assessments are largely of a critical-thinking nature designed to determine students' ability to deploy acquired knowledge to new situations, which is a key graduate attribute for successful physics-trained graduates.

3. Strategies and approaches to learning

3.1 Learning and teaching activities

Assumed Knowledge

Pre-requisite(s): PHYS4141 Quantum Mechanics (Honours), and PHYS4142 Statistical Physics (Honours)

Timetable

Lectures: 3 hours per week (Weeks 1-5, 7-10) – Please see detailed module descriptions for class

Seminar: 1 hour per week (Week 1-5, 7-10) – Wednesday 1500-1600, OMB G32

3.2 Expectations of students

We believe that effective learning is best supported by a climate of enquiry, in which students are actively engaged in the learning process. To ensure effective learning, students should participate in class. Effective learning is achieved when students attend all classes, have prepared effectively for classes by reading through previous lecture notes, in the case of lectures, and, in the case of tutorials or laboratories, have made a serious attempt at doing the problems or pre-work themselves prior to the class. Furthermore, lectures should be viewed by the student as an opportunity to learn, rather than just copy down lecture notes. Effective learning is achieved when students have a genuine interest in the subject and make a serious effort to master the basic material.

Academic misconduct will not be tolerated in any form in this course. Substantiated instances of cheating, plagiarism or copying answers may result in a failure grade or significant deduction of marks. Please see https://student.unsw.edu.au/plagiarism if you are in any way unsure of what constitutes plagiarism. Assignments in this class are to be done independently.

4. Course schedule and structure

Module 1: Advanced Astrophysics

Detailed syllabus

Part 1. Atomic & Molecular Physics, & Radiative Transfer:

Atomic energy levels, allowed and forbidden transitions, partition functions, spectra of hydrogenic atoms, Lorentz and Voigt line profiles. Molecular energy levels and Gaussian profiles, Doppler broadening, pressure broadening.

Conditions for local and nonlocal thermodynamic equilibrium. Hot gases: ionization and the Saha equation; cool gases: chemical equilibrium, condensate formation. Single scattering albedo and phase function. Rayleigh scattering, electron scattering.

Basic processes of absorption, emission and scattering, optical depth. The radiative transfer equation. Spectral line formation, including the effects of opacity, macro-turbulence and physical conditions on line formation. Examples of line formation in warm and cool atomic gas, and in molecular gas.

Part 2. Exoplanets:

Planet formation: conditions in the protostellar disk, condensation temperature, self- shielding, accretion, collisions and scattering, planetary migration and angular momentum transfer. Methods for detecting exoplanets: radial velocity, transits, microlensing, astrometry, observational biases, detecting planetary atmospheres.

Part 3. Asteroseismology:

Asteroseismic studies of solar-like oscillators: interior structure, composition, rotation, magnetic field, observational limits.

Part 4. Interstellar Medium and Star Formation:

HI in galaxies: hyperfine structure, rotation curves, column density. The phase transition between warm and cool HI, and the formation of molecular gas. HII regions: density, temperature, photoionization, recombination, forbidden transitions, Stromgren radius.

The role of turbulence and magnetic fields in the interstellar medium, gravitational collapse, Jeans mass, radiative cooling. Initial mass function. Kennicutt-Schmidt law, core ignition, accretion, Eddington limit, timescales.

Part 5. Galaxy formation and evolution:

Orbital dynamics, conservation laws, violent relaxation, stellar populations, galactic chemical evolution. Hierarchical galaxy formation (simulated vs observed), merger trees, galaxy assembly, scaling laws, baryon cycle

Part 6. Time-Domain Astrophysics:

Transient phenomena including supernovae, gamma-ray bursts, and the first stars. Gravitational waves (their detection, and models for the originating objects)

Part 7. Advanced statistical techniques:

Gaussian mixture modeling, Bayesian statistics, Monte Carlo sampling, forward modelling.

Textbooks:

Excerpts from appropriate graduate-level textbooks and current research publications will be used as the materials for this course. Current textbooks relevant to these topics are available in the School textbook collection, including:

Clayton, Principles of Stellar Evolution and Nucleosynthesis

Carroll & Ostlie, An Introduction to Modern Astrophysics

Kippenhahn, Weigert, Weiss, Stellar structure and evolution

Binney & Tremaine, Galactic dynamics

Binney & Merrifield, Galactic astronomy

Class Timetable

Monday 10:00-12:00 (Weeks 1-4,7-10, OMB150)

Wednesday 12:00-1:00 (Weeks 1-4,7-10, OMB150)

Module 2: General Relativity

Detailed syllabus

Part 1: Revision of special relativity (2 hours)

Hartle Ch. 4 & 5 Spacetime;

Lorentz transformation; Four-vectors; Special relativity kinematics and dynamics; Variational principle for free particle motion; Light rays

Part 2: Gravity as geometry (5 hours)

Hartle Ch. 6, 7 & 8

The equivalence principle; Clocks in a gravitational field: heuristic considerations; Specifying geometry with a metric; Newtonian gravity in spacetime/geometry terms;

Local inertial frames and freely falling frames; Light cones and worldlines; Vectors in curved spacetime; Geodesic equation; Riemann normal coordinates

Part 3: Geometry outside a spherical object (4 hours)

Hartle Ch. 9 & 12

Schwarzschild geometry; Gravitational redshift; Particle orbits and precession of the perihelion; Light ray orbits and deflection; Schwarzschild black hole; Collapse to a black hole; KruskalSzekeres Coordinates

Part 4: The Einstein equation (6 hours)

Hartle Ch. 20, 21 & 22

Vectors and Dual vectors; Tensors; The covariant derivative. Free falling frames; Tidal gravitational force; Equation of geodesic deviation; Riemann curvature; Einstein equation in vacuum; 7 Schwarzschild metric derivation; Density as a source of curvature; Stress-energy tensor; Conservation of energy-momentum; Einstein equation; The Newtonian limit

Part 5: Gravitational waves (3 hours)

Hartle Ch. 16 & 23

Linearised gravity in vacuum; Traceless transverse gauge; Linearised Einstein equation with sources; General solution; Gravitational wave production and emission; Gravitational radiation from binary stars; Quadrupole formula; Energy in gravitational waves; Detecting gravitational waves; Gravitational wave interferometers

Part 6: Cosmology (4 hours)

Hartle Ch.17 & 18

Cosmological principle; Geometry of a homogeneous and isotropic space; FLRW spacetime and dynamic; Cosmological redshift; Distances and horizons; Inferring distances from observations; Energy content; Friedmann equation; Matter and radiation domination; The age of the universe

Textbooks:

Primary: J. B. Hartle, Gravity, An Introduction to Einstein's General Relativity

Secondary: S. M. Carroll, An Introduction to General Relativity, Spacetime and Geometry Class

Timetable

Monday 1400-1600 (Weeks 1-4, 7-10, OMB G32)

Wednesday 1300-1400 (Weeks 1-4, 7-10, OMB 150)

Module 3: Quantum Field Theory

Detailed syllabus

Introduction: what is QFT and its relation to many body physics?

Part 1: Classical theory of relativistic fields, 2 hours.

Klein-Gordon equation (revision); Lagrangian and Hamiltonian formalisms; Lorentz invariance; Noether's theorem and conserved currents; Symmetries and groups.

Part 2: Free fields, 4 hours

Canonical quantisation of real scalar field; ultraviolet divergence of vacuum energy; the cosmological constant, Casimir effect; Particles, relativistic normalisation; Complex scalar fields and antiparticles; the Heisenberg picture; Causality, propagators, Green's functions; Dirac fermions.

Part 3: Interacting Fields, 4 hours.

Lehmann-Symanzik-Zimmermann reduction formula; The Interaction Picture; Greens functions in field theory. Vertex functions and ideas of the diagrammatic technique, Feynman diagrams; Scattering amplitudes (phi^4 theory); S-matrix; Connected diagrams and vacuum bubbles; Cross sections and decay rates.

Part 4: Two-point Green's function, 2 hours.

Lehmann - Källén spectral representation; Virtual corrections; Renormalisation 8

Part 5: Path Integral Approach, 8 hours.

Introduction of path integral formulation, path integral approach for many-body systems. Imaginary time formalism. Instantons. Matsubara technique. Wess-Zumino topological terms. False vacuum decay, lifetimes of metastable states. Strongly interacting fermions. Bosonization.

Part 6: Topological objects in field theory, 4 hours.

Non-linear sigma model, relevance to quantum antiferromagnets and to the chiral breaking in vacuum. Topological solutions in bosonic field theories. Skyrmions, hopfions. Experimental observations.

Textbooks

Srednicki, Quantum Field Theory Schwartz, Quantum Field Theory and the Standard Model

Altland and Simons, Condensed Matter Field Theory

Sidney Coleman, Aspects of Symmetry

Peskin and Schroeder, An Introduction to Quantum Field Theory Ryder, Quantum Field Theory

Class Timetable

Tuesday 1100-1300 (Weeks 1-4, 7-10, OMB 150)

Thursday 0900-1000 (Weeks 1-4, 7-10, OMB 150)

Module 4: Quantum matter, Information and Computing

Detailed syllabus

Part 1: Renormalisation group (RG) for classical and quantum systems (8 hours)

RG in classical dynamical models: transition to chaos; anomalous diffusion

RG for phase transitions in classical statistical mechanics

RG for quantum lattice models; Density matrix renormalization group; Matrix product states; Quantum entanglement; Entanglement renormalization; Multi-scale entanglement renormalization ansatz states

Part 2: Quantum Error Correction & Quantum Phases (4 hours)

Basics of quantum error correction

Stabilizer quantum error-correcting codes

Relationship between stabilizer error-correcting codes and quantum phases

Part 3: Quantum Hall & Topological Effects (4 hours)

Charged particle in an electromagnetic field Landau levels and filling factor

Integer quantum Hall effect Edge states and topology

Fractional quantum Hall effect and composite fermions

Part 4: Quantum Computing (8 hours)

Universal set of quantum gates Basic gates - AND, NOT, CNOT

Fundamental constraints: no-cloning theorem Quantum error correction: Shor algorithm Making a quantum dot spin qubit

Single-qubit operations - sigma_x and sigma_z gates; ESR, EDSR (briefly) Two-qubit operations - exchange, coupling to a resonator, dipole-dipole Theory of decoherence

Relaxation: T1 and phonons Dephasing: T2, phonons and noise Spin-echo, pulse sequences Fidelity, randomised benchmarking

Advanced Topics (if time permits)

Tensor networks Topological quantum phases

"It from qubit" — Error-correcting codes and the ADS-CFT correspondence

Class Timetable

Thursday 1300-1500 (Weeks 1-4, 7-10, OMB 150)

Friday 1400-1500 (Weeks 1-4, 7-10, OMB 150)

5. Assessment

5.1 Assessment tasks

Course assessment comprises assignments, in-session test, laboratory and final examination.

Assessment task	Length	Weight	Mark	**Due date** *(normally midnight on due date)*
Assessment 1: Journal Club Presentation	40 mins	10%		TBA at Seminar
Assessment 2: Assignment 1		20%		Friday 25th June (Week 4)
Assessment 3: Assignment 2		20%		Friday 30th July (Week 9)
Assessment 4: Final Exam	2 hours	50%		See Exam Schedule - TBA

Information about Special Consideration is available from https://student.unsw.edu.au/special-consideration

Further information
UNSW grading system: student.unsw.edu.au/grades
UNSW assessment policy: student.unsw.edu.au/assessment

5.2 Assessment criteria and standards

Please see Moodle for a marking rubric for each assessment task.

5.3 Submission of assessment tasks

Assignment Submissions

Unless otherwise specified, assignments should be submitted online by 5pm on the due date.

A downloadable assignment cover sheet is available from https://www.physics.unsw.edu.au/current-students/cover-sheet

Marks will be deducted for late assignments, at a rate of 5% of the maximum possible mark for the assignment per day. A weekend will count as two days. An assignment submitted after the solutions have been posted will automatically receive 0%.

5.4. Feedback on assessment

Please see Moodle for details on how feedback will be provided for each assessment task

6. Academic integrity, referencing and plagiarism

Referencing is a way of acknowledging the sources of information that you use to research your assignments. You need to provide a reference whenever you draw on someone else's words, ideas or research. Not referencing other people's work can constitute plagiarism.

Further information about referencing styles can be located at student.unsw.edu.au/referencing

Academic integrity is fundamental to success at university. Academic integrity can be defined as a commitment to six fundamental values in academic pursuits**:** honesty, trust, fairness, respect, responsibility and courage.[1] At UNSW, this means that your work must be your own, and others' ideas should be appropriately acknowledged. If you don't follow these rules, plagiarism may be detected in your work.

Further information about academic integrity and **plagiarism** can be located at:

- The *Current Students* site student.unsw.edu.au/plagiarism*,* and
- The *ELISE* training site subjectguides.library.unsw.edu.au/elise

The *Conduct and Integrity Unit* provides further resources to assist you to understand your conduct obligations as a student: student.unsw.edu.au/conduct.

7. Readings and resources

See detailed syllabus of each stream for textbooks and readings.

Lecture Notes Supplied with Course

8. Administrative matters

Communications
Students should check their UNSW email account regularly as all official university communication will be sent to that address. Students should use their university email account when writing to UNSW staff and should always include their name and student number.

Health and Safety

[1] International Center for Academic Integrity, 'The Fundamental Values of Academic Integrity', T. Fishman (ed), Clemson University, 2013.

The School of Physics is actively committed to the health, safety and welfare of its staff and students. Information on relevant UNSW Occupational Health and Safety policies and expectations is available at: www.ohs.unsw.edu.au and https://www.physics.unsw.edu.au/about/safety

Recommended Internet Sites
The School of Physics website is www.physics.unsw.edu.au. Under the "Current Students" link students will find information about degrees, courses, and assessment.
The University website my.unsw.edu.au provides links to the UNSW Handbook, Timetables, Calendars and other student information.

Student Complaint Procedures
UNSW has procedures for dealing with complaints. These aim to solve grievances as quickly and as close to the source as possible. Information is available here: student.unsw.edu.au/complaints. Staff who can assist include:

School Contacts:

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9. Additional support for students

- The *Current Students* Gateway: student.unsw.edu.au
- Academic Skills and Support: student.unsw.edu.au/skills
- Student Wellbeing, Health and Safety: student.unsw.edu.au/wellbeing
- Disability Support Services: student.unsw.edu.au/disability
- UNSW IT Service Centre: www.it.unsw.edu.au/students